MINOR STUDIES FROM THE PSYCHOLOGICAL LABORATORY OF CORNELL UNIVERSITY

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XXIV. ON THE VARIATION WITH TEMPERATURE OF THE PITCH OF WHISTLES AND VARIATORS

By G. J. RICH

We recently had occasion to tune a set of Stern tone-variators by comparison with tuning-forks. When the comparison was repeated, a day or two later, the series proved to be slightly out of tune; and this occurred several times. It was natural to think that the change was due to change in the temperature of the room; and reference to works on physics showed that such a variation in pitch might be the result of variation in temperature. It is the purpose of this paper to show this dependence of pitch on temperature, and to set forth the precautions that must therefore be taken in calibrating a whistle or variator.

In the numerous articles which have dealt with the construction, use, and accuracy of these instruments, the influence of temperature has been neglected; and this in spite of the fact that it has been recognized in discussions of the pitch of organ pipes. Ellis[1] mentions that organ pipes change in pitch with temperature, and (as will be noted later) gives a formula for correction. Galton,[2] in describing his whistles, gives a formula for their pitch, which is, he says, valid for ordinary conditions of temperature. But only three of the later writers recognize that temperature-conditions are not always 'ordinary.' Stumpf and Meyer,[3] speaking of a Galton whistle blown by compressed air, say that the compression-apparatus must not be used for too long a time without interruption, because the temperature of the air-stream will change, and cause a slight change in the tone. Myers[4] records as an objection to the Stern variator its sensitivity to slight changes in temperature. But Appunn,[5] Stumpf,[6] Melde,[7] Schwendt,[8] Schulze,[9] Hegener,[10] and Jones,[11] in discussing the ac-

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[1] Helmholtz, *Sensations of Tone,* 1895, 89, footnote.

[2] *Inquiries into Human Faculty,* 1883, 375.

[3] *Ann. d. Phys. u. Chem.* (Wiedemann), 61, 1897, 760; 64, 1898, 409.

[4] *Mind,* N. S., 20, 1911, 285.

[5] *Ann. d. Phys. u. Chem.* (Wied.), 67, 1899, 217.

[6] *Ibid.,* 68, 1899, 105.

[7] *Ibid.,* 67, 1899, 781.

[8] *Archiv für Ohrenheilkunde,* 49, 1900, 1; *Verhandlungen der Gesell. deutscher Naturf. u. Aerzte,* 71, 1900, 369; *Verhandl. d. deutsch. otologischen Gesell.,* 9, 1900, 55.

[9] *Ann. d. Phys.* (Drude), 13, 1904, 1066; 24, 1907, 784.

[10] *Verhandl. d. deutsch. otologischen Gesell.,* 17, 1908, 79; 72.

[11] *Edinburgh Medical Journal,* 11, 1902, 349.

curacy of Galton whistles, make no mention of temperature. In other papers, Schwendt,[12] Schulze,[13] Myers,[14] and Titchener,[15] using Kundt's dust-figures, Quincke's tubes, or sensitive flames in the determination of the pitch of whistles, have made corrections for temperature in the constants used to calculate frequency from the crude data, but have taken no account of a temperature-change in frequency itself. Edelmann,[16] using Kundt's method, makes no correction for temperature, but takes as his constant that for average temperature. Stern,[17] in describing his variators, makes no mention of the dependence of pitch on temperature.

In a Galton whistle, or in any form of piston-whistle, as well as in a Stern variator, we have, of course, a vibrating body of air. For such a body, it follows from the theory of dimensions[18] that frequency is proportional to $\frac{\sqrt{p/d}}{L}$, p being the pressure and d the density of air, $\sqrt{p/d}$ the velocity of sound in air,[19] and L any length of the containing chamber. Inserting an arbitrary constant, we get for N, the frequency of our whistle:[20]

$$N = C\frac{v}{L},$$

where C is constant for all geometrically similar containing chambers.

But v, the velocity of sound in air, changes with temperature. Watson[21] gives the following formula for v_t, the velocity at temperature t, when v_o, the velocity at 0°, is known:

$$v_t = v_o\,(1+.0018t).$$

This gives us:

$$N = C\frac{v_o\,(1+.0018t)}{L}.$$ [22]

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[12] *Arch. f. ges. Physiol.*, 71, 1899, 346; *Ver. d. naturf. Ges. in Basel*, 12, 1900, 149.

[13] *Ann. d. Phys. u. Chem.* (Wied.), 68, 1899, 99; 869.

[14] *Jour. of Physiol.*, 28, 1902, 417.

[15] *Proc. Amer. Phil. Soc.*, 53, 1914, 328.

[16] *Ann. d. Phys.* (Drude), 2, 1900, 469; *Zeit. f. Ohrenheilkunde*, 36, 1900, 330.

[17] *Zeit. f. Psychol.*, 11, 1896, 4; 21, 1899, 361; 30, 1902, 422; *Verhandl. d. physik. Gesell. su Berlin*, 16 Jahrgang (4), 1897, 42; *Psychol. der Veränderungsauffassung*, 1898, 82.

[18] This use of the theory of dimensions is justified by Rayleigh, who employs it for the frequency of strings. *Theory of Sound*, 1877, i, 139. For this method of deriving the formula I am indebted to Dr. J. Slepian of the Department of Mathematics, Cornell University.

[19] Watson, *A Text-Book of Physics*, 364.

[20] Since N is proportional to $\frac{v}{L}$, it is equal to a constant *times* this. The constant we have not determined. It depends on the shape of the containing chamber, and the direction in which the measurement L is taken.

[21] Watson, *op. cit.*, 367.

[22] This is, save for the constants, practically the formula given for the dependence of the pitch of organ-pipes on temperature. Barton, *Text-Book on Sound*, 252.

It remains to show that C and L do not change appreciably with temperature. When a whistle-pipe or variator-cylinder expands with temperature, it does so in all directions, and remains geometrically similar at all temperatures; and we have seen that C is constant under just these conditions. L varies with any linear dimension of the pipe. Now most whistles are made of brass. The coefficient of linear expansion of this metal is .000019.[23] But the coefficient of change of the velocity of sound in air with temperature is, as we have seen, .0018. Thus the change in length is only about one one-hundredth of the change in velocity, and may be considered negligible in comparison with the latter. For other metals, the coefficient of expansion is of the same order.

Since C and L do not change, N must vary directly with v, and must have the same coefficient of change with temperature, namely .0018. This means that the frequency changes .0018 or .18% for each degree of change in temperature, and gives us the following formula for N_a, the frequency at temperature t_a, when we know N_b, the frequency at the temperature t_b:

$$N_a = N_b\,[1 + .0018\,(t_a - t_b)\,].$$

By means of this formula we can make any correction for temperature.

Ellis[24] gives a similar formula, for Fahrenheit temperature, in which the coefficient is .00104. If we change this to centigrade by the equation: $1°C = 9/5°\ F$, it becomes .00187, which is practically our coefficient.

Such a variation in pitch is by no means negligible. This is readily seen from the following table, which gives the magnitude of the variation at various parts of the scale for 1° and for 10°. A room is liable to vary in temperature, from day to day, as much as this latter amount.

Pitch in *vs.*	Variation in *vs.*	
	1°	10°
100	.18	1.8
500	.9	9.
800	1.4	14.
1000	1.8	18.
5000	9.	90.
10000	18.	180.
30000	54.	540.
50000	90.	900.

Let us now turn to the calibration of whistles and variators. If we are using a graphic method, such as the Marbe smoke-rings, we get a record of actual frequency at the temperature at which the determination is made. But if we are to compare a series of determinations (at different parts of the scale, for example), we must correct for temperature by reducing the frequencies obtained to the

[23] Watson, *op. cit.*, 299.

[24] *Loc. cit.*

frequencies at some standard temperature. This may be readily done by the type of formula given above, namely:

$$N_s = N_r\,[1+.0018\,(t_s - t_r)\,],$$

where t_r = temperature at which determination is made.
t_s = standard temperature.
N_r = frequency determined at temperature t_r.
N_s = frequency at standard temperature t_s.

We may next consider calibration by comparison with a source of known frequency (setting by beats). If we use some source which does not vary with temperature, like a siren, which is dependent only on speed of rotation, we get a direct determination for the temperature at which we are working; and this can be reduced to the frequency at a standard temperature in the manner described above for use with a graphic method. But most of our sources of tone vary with temperature. A tuning fork, which is a usual standard source, varies .000112 of its frequency for each degree of change in temperature.[25] This is about one-twentieth of the variation of a pipe, and may usually be considered negligible in comparison with the latter. If, however, it is desired to make this correction, the temperature for which the frequency of the fork is stated must be known.

But when we compare with another whistle, pipe, or variator, the correction for temperature of the standard is no longer negligible. For all we know about our standard is that it gives a certain frequency at a certain temperature. Now let t_q be the temperature at which our known source has a frequency N_q. Then at the temperature t_r, at which the comparison is made, it will have the frequency N_r ; which, since the instrument is a wind instrument, is given by:

$$N_r = N_q\,[1+.0018\,(t_r - t_q)\,].$$

We set the instrument to be calibrated so that it has this same frequency, N_r. We must then reduce this to N_s, the frequency at the standard temperature, t_s, for which we are going to calibrate our unknown whistle or variator. We proceed as follows:

$$\begin{aligned} N_s &= N_r\,[1+.0018\,(t_s - t_r)\,]. \\ &= N_q\,[1+.0018\,(t_s - t_r)\,]\,[1+.0018\,(t_r - t_q)\,] \\ &= N_q\,[1+.0018\,(t_s - t_r)+.0018\,(t_r - t_q)+(.0018)^2(t_s - t_r)\,(t_r - t_q)\,]. \end{aligned}$$

But the factor $(.0018)^2(t_s - t_r)(t_r - t_q)$ is negligible, and is, in fact, neglected in practice. Therefore

$$\begin{aligned} N_s &= N_q\,[1+.0018\,(t_s - t_r)+.0018\,(t_r - t_q)\,]. \\ N_s &= N_q\,[1+.0018\,(t_s - t_q)\,]. \end{aligned}$$

This expression does not involve t_r, the temperature at which the comparison was made. This means that we can make our comparison regardless of the room temperature, and then calculate the frequency of our unknown source for any temperature we may care to assume (t_s). In the special case, where we want to calibrate our unknown for the same temperature as that for which the known source is calibrated, $t_s = t_q$, and no correction for temperature is necessary. Of course, this all assumes that both sources of tone are blown at the same temperature.

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[25] Barton, *op. cit.*, 299.

This independence of the temperature at which the work is done also holds for calibration by the method of Kundt's dust-figures. For the frequency calculated by this method is:[26]

$$N = \frac{v}{2l}$$

where $v =$ velocity of sound in air at the existing temperature
$l =$ distance between nodes.
But this is the frequency given by the whistle; and if it is blown at the same temperature, this is:

$$N = \frac{Cv}{L}$$

therefore

$$\frac{Cv}{L} = \frac{v}{2l}$$

and

$$\frac{C}{L} = \frac{1}{2l}$$

since the velocities are equal, being those of air at the same temperature. This shows us that, in calibrating a wind instrument, the distance between the nodes depends only on the construction of the instrument, and is independent of the temperature, provided that both the dust-tube and the source of sound are at the same temperature. This is, indeed, to be expected; for the frequency of the whistle or variator varies directly as the velocity of sound in air, which is the factor that varies with temperature. And the frequency varies similarly when calculated from the dust-piles. Therefore they both vary together for any change in temperature, and the ratio of the other factors must needs remain constant. This is the same independence of the temperature at which the determination is made that we found in the case of comparison with a wind instrument of known frequency. For any given whistle, we get the same L at any temperature. We may therefore assume that it was obtained at the temperature for which we desire to calibrate our whistle, t_s, and may then calculate accordingly, by the formula:

$$N = \frac{v_s}{2l}$$

where $v_s =$ velocity of sound in air at temperature t_s.

$$\begin{aligned} v_s &= v_o + 61\ t_s. \\ &= 33150 + 61 t_s \\ &= 33150\ [1 + .0018\ (t_s - 0)\ ]. \end{aligned}$$

All of these methods give us calibrations of our whistle or variator at some standard temperature, t_s. If it is used at some other temperature (t_p), it is merely necessary to correct for that temperature

[26] *Ibid.*, 534.

in order to get the actual frequency. This can be done by the formula:

$$N_p = N_s\,[1+.0018\,(t_p-t_s)\,].$$

To sum up, it has been shown: (1) that the frequency of a whistle or variator varies appreciably with temperature; (2) that temperature must be taken into account in calibrating one of these instruments; (3) that calibrations at different settings must be reduced to a standard temperature to be comparable; (4) that in calibrating by comparison with another wind instrument the temperature at which the comparison was made need not be considered, since both instruments vary to the same amount with temperature; but that the results of such a comparison are valid only for the temperature for which the standard was calibrated, unless a correction be made; and (5) that in calibrating by Kundt's method the temperature at which the determination is made is likewise of no account, the results being valid for the temperature for which the velocity of sound is taken in computing the frequency. Moreover, (6) formulae have been given for performing the various corrections.

XXV. Visual Quality as a Determinant of Clearness

By J. S. Smith

Are there certain color-qualities which make a special appeal to attention? If, for example, red and yellow were to appear simultaneously in the visual field, should we tend definitely to regard the one and to disregard the other; or, in general, is there any visual quality to which we are predisposed to attend? Gale[1] found that black on a white, and green on a black background are most effective for men, while for women red is the attracting color irrespective of background. But Gale apparently made no attempt to control the time of exposure, or to avoid successive contrast, adaptation, and the space-error. Furthermore, he employed only artificial illumination, and he failed to take introspections. It seemed advisable, therefore, to repeat the experiment.

Method and Apparatus.—We employed the method of paired comparisons. The stimuli were six colors of the Milton Bradley Spectral Scales: red (R), orange (O), yellow (Y), green (G), blue (B), violet (V), together with black (Bk) and white (W). These we mounted in one-inch squares, half an inch apart, on both black and white cards, five by eight inches; the black square was mounted on white, and the white square on black. The stimuli were presented in the Whipple tachistoscope, with an exposure of 160 sigma, in both daylight and artificial light, with dark adaptation. Care was taken that no color should appear in consecutive exposures. Since every color was presented with every other color on each background, there were 21 pairs of stimuli in each set. The cards were also shown inverted, to avoid any space error; so that for each illumination there were 42 observations with each background. Finally, every

[1] H. Gale, *Psychological Studies,* 1900, 55 ff.